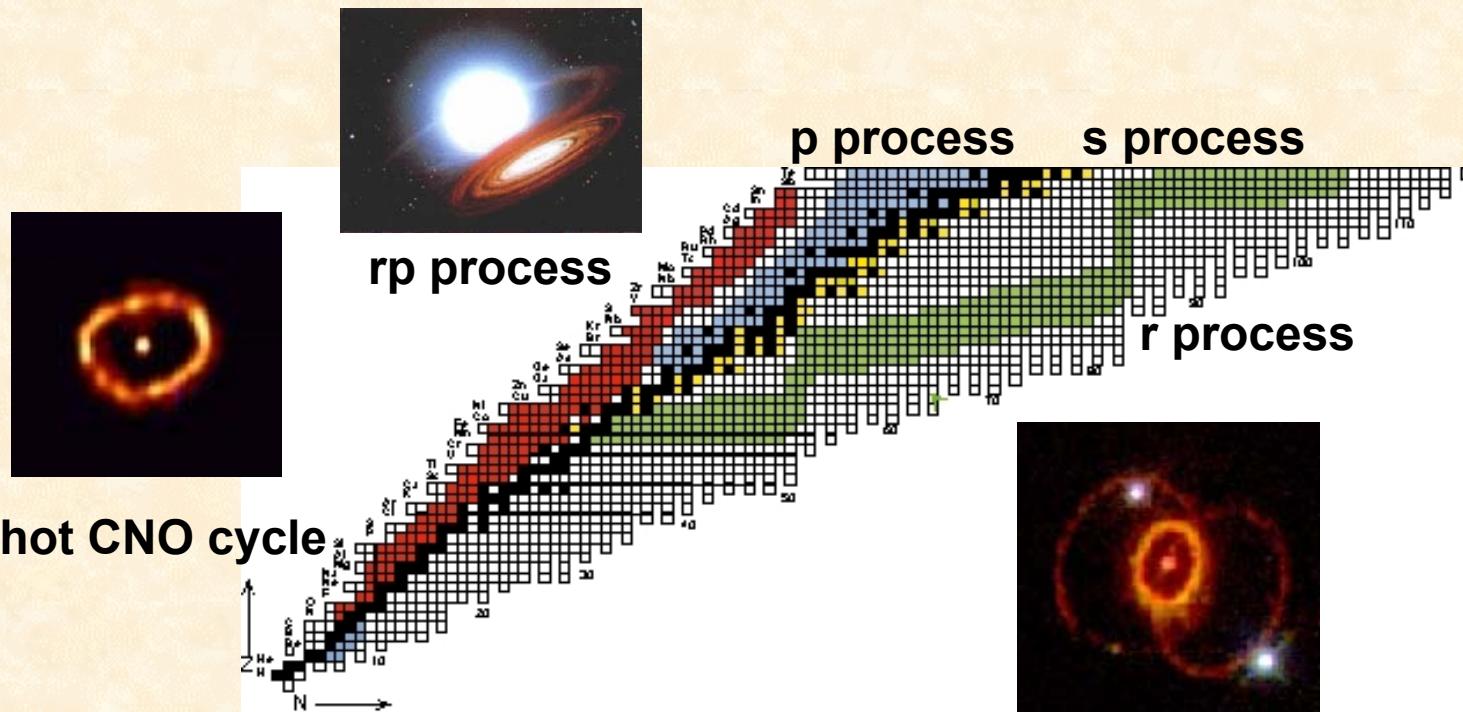


# Nucleosynthesis in Stellar Explosions

**Jeff Blackmon ~ Physics Division, ORNL**

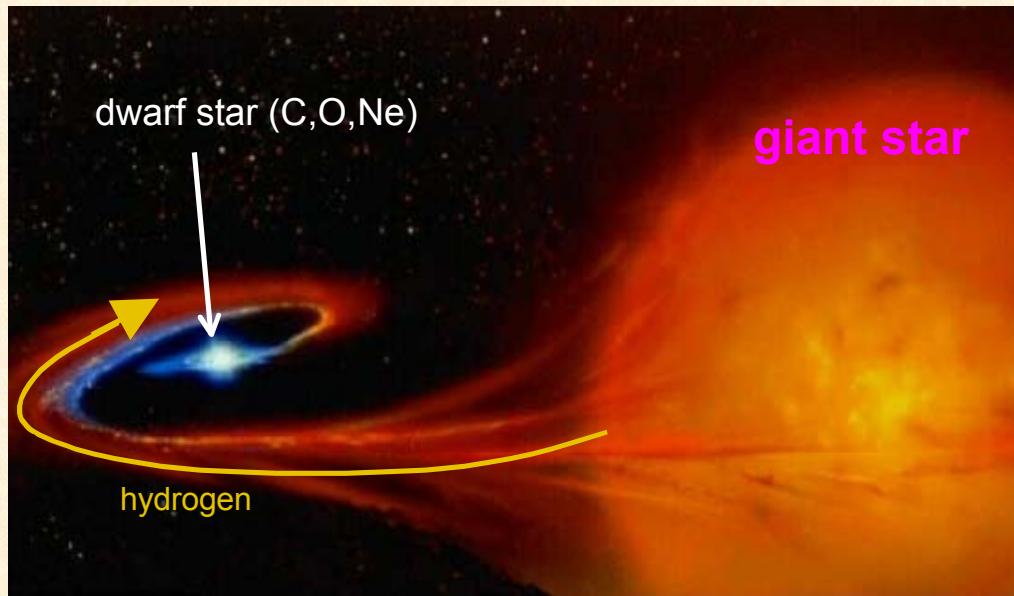
- Novae
- X-ray Bursts
- Supernovae



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 **UT-BATTELLE**

# Novae

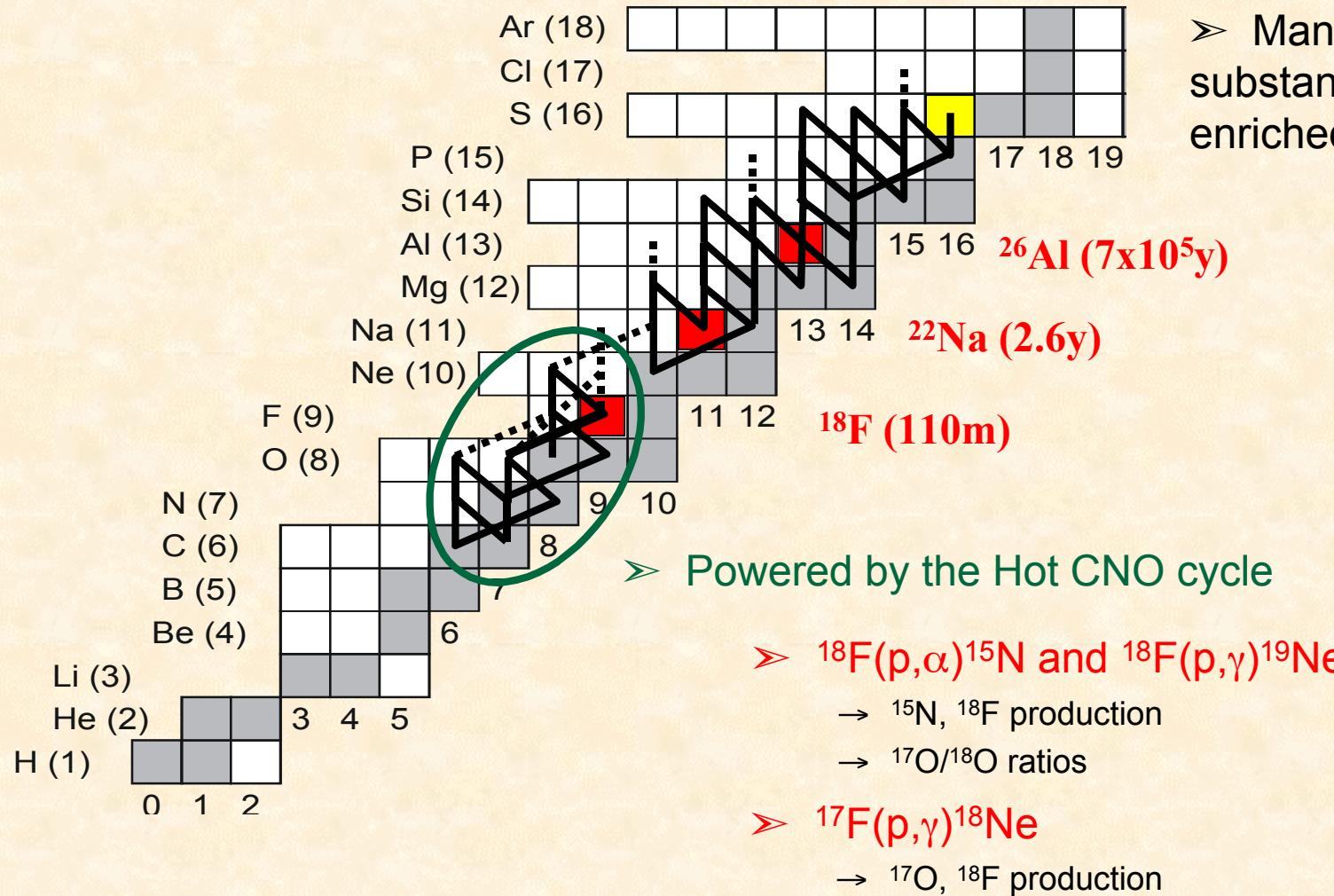


- 2-3 / month in our Galaxy
- New observational tools
  - Chandra, Integral
  - Meteoritic grains
- More realistic models under development
- Some large nuclear physics uncertainties

- Mass transferred from less massive star (red giant) to white dwarf companion
- Hydrogen gas burns explosively with CNO nuclei
  - thermonuclear explosion
- Elements as heavy as calcium may be synthesized
- Likely source of  $^{15}\text{N}$ ,  $^{17}\text{O}$

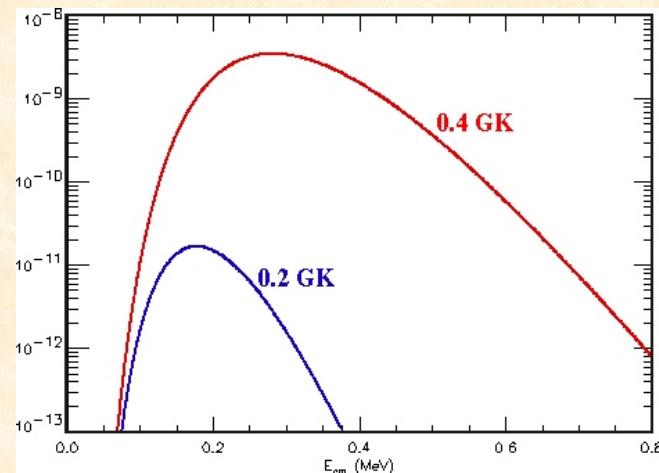


# Nova Nucleosynthesis

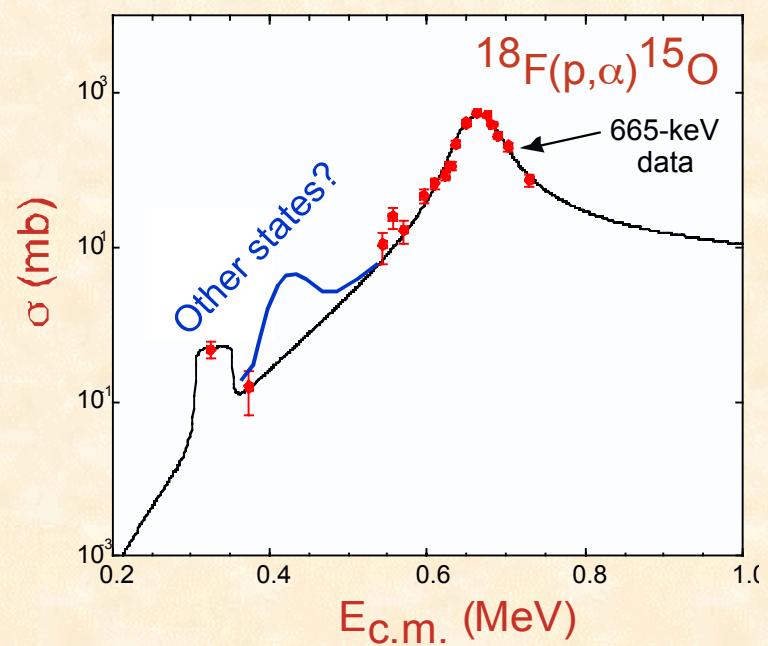
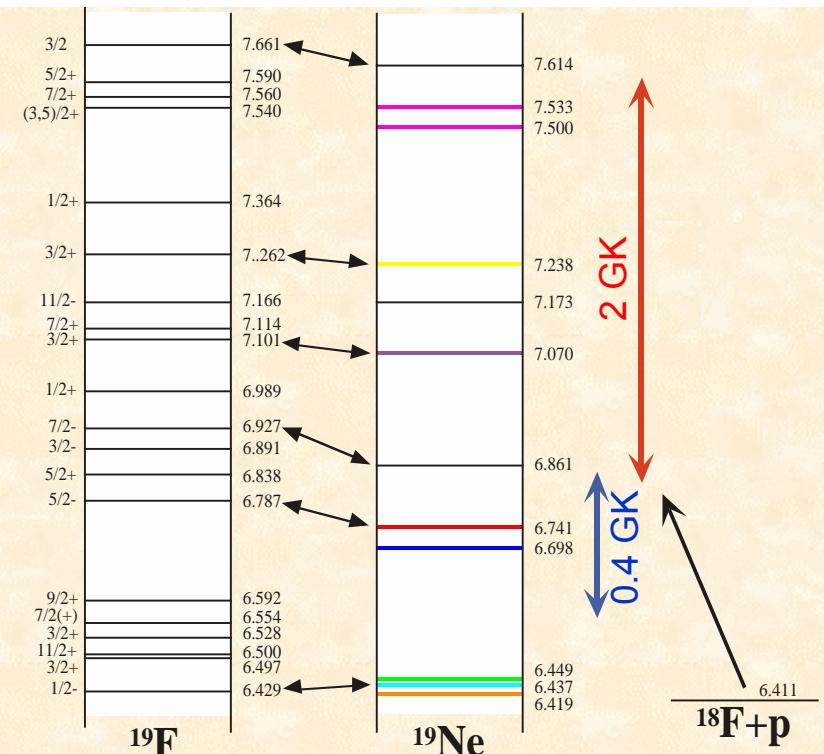
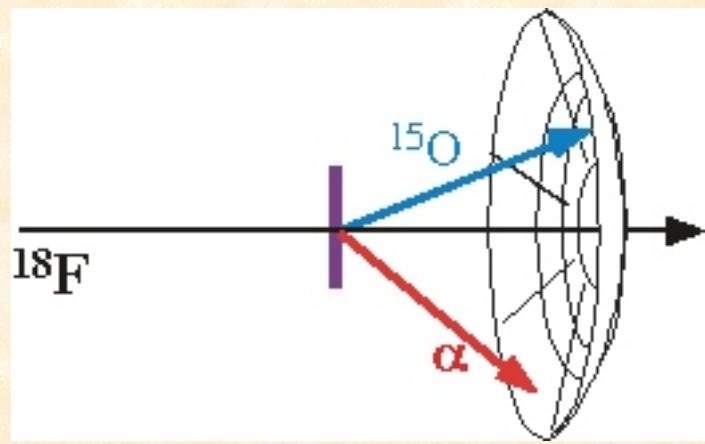


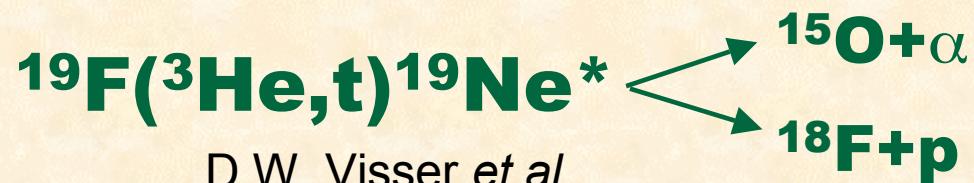
# $^{18}\text{F}(\text{p},\alpha)^{15}\text{O}$

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{3/2} \int_0^{\infty} \sigma E e^{-E/(kT)} dE$$

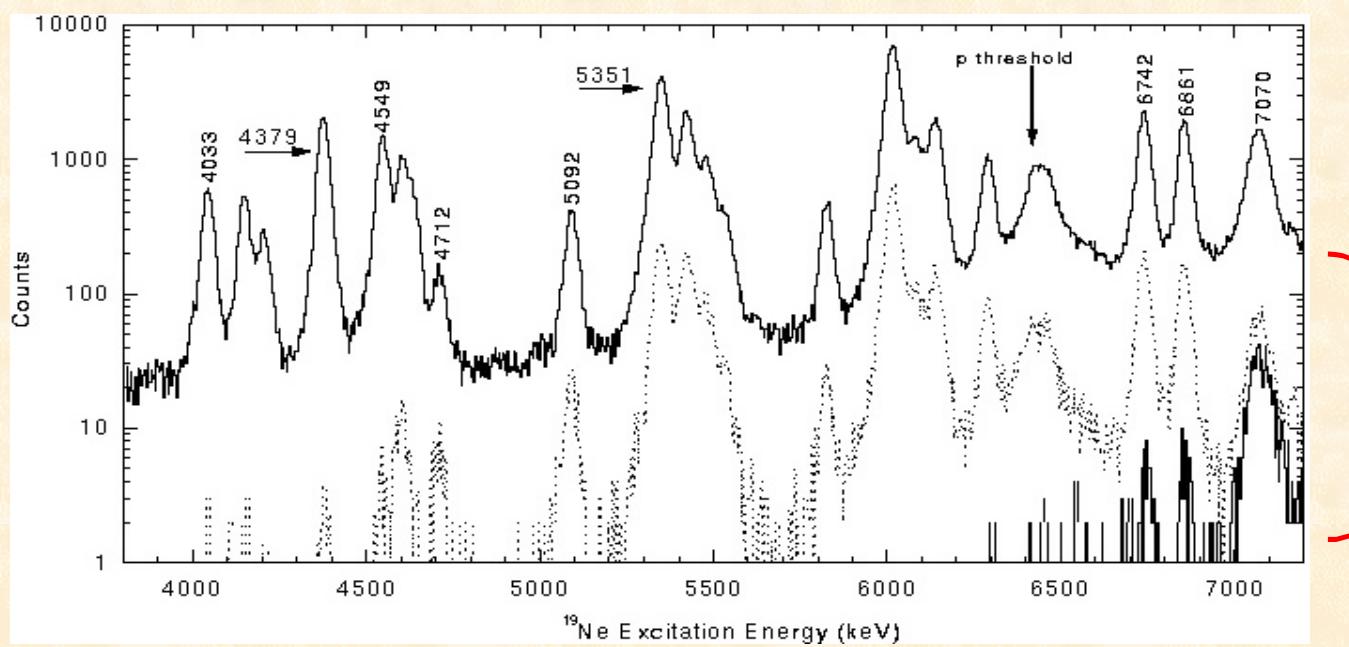
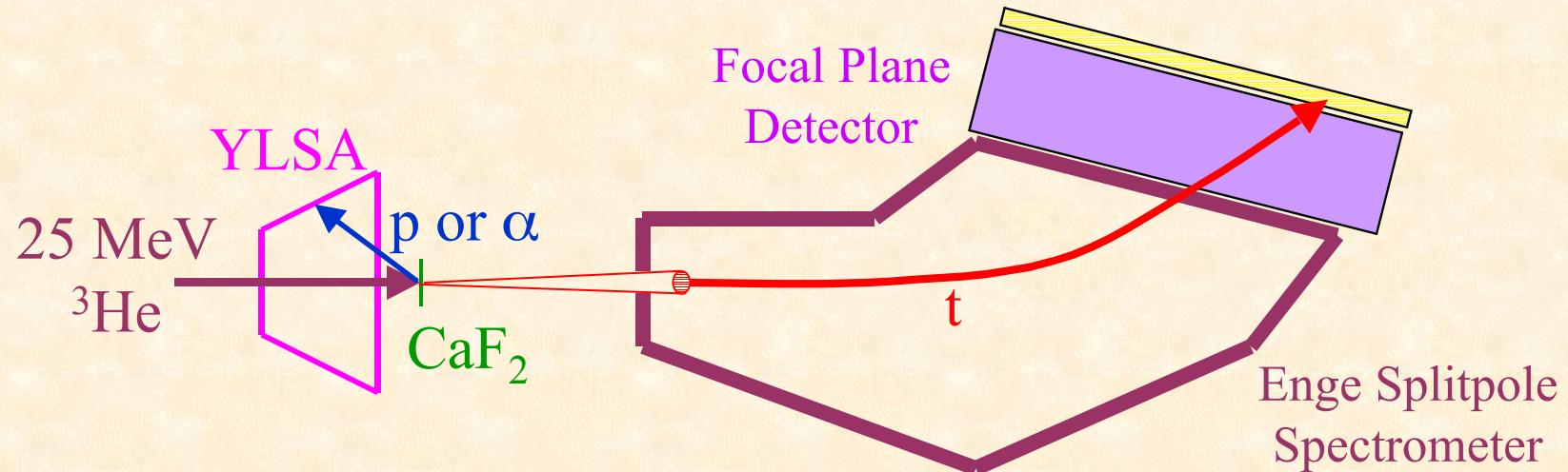


➤ HRIBF Measurement (Bardayan et al.)



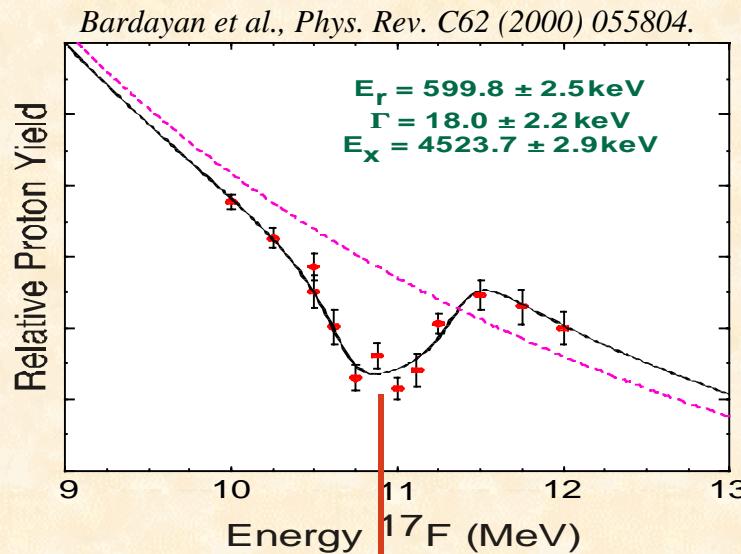


D.W. Visser et al.



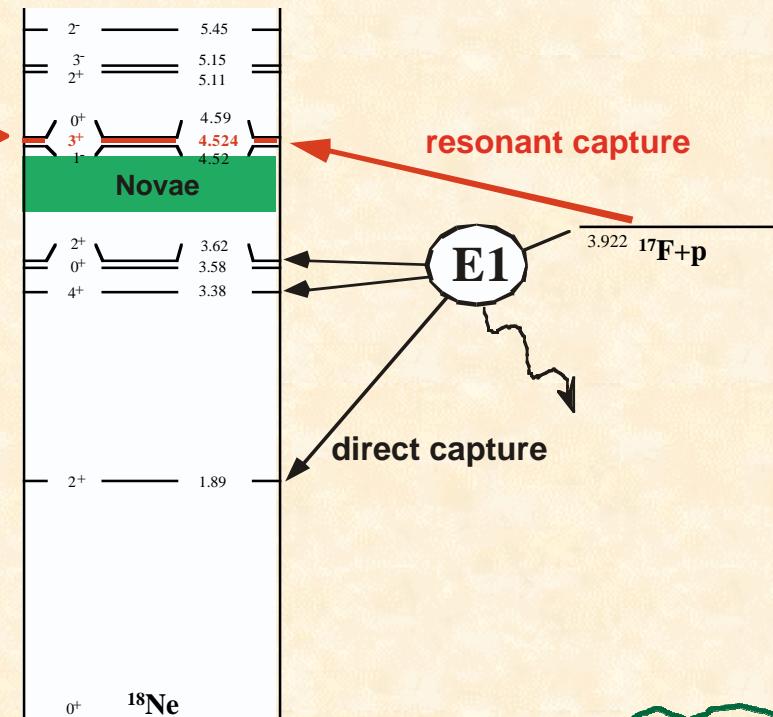
$$\frac{\Gamma_p}{\Gamma} \quad \& \quad \frac{\Gamma_\alpha}{\Gamma}$$

# The $^{17}\text{F}(\text{p},\gamma)^{18}\text{Ne}$ Reaction Rate

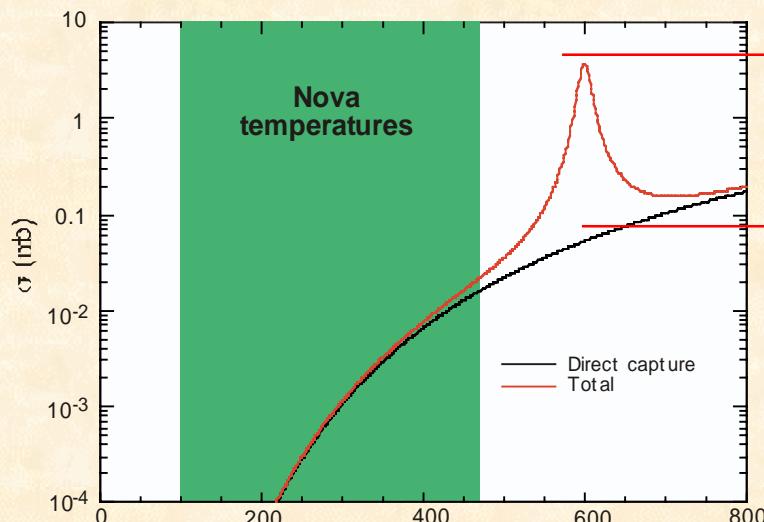


- 3+ Found via  $^{17}\text{F}+\text{p}$  scattering
- Only two significant contributions to the rate:
  - 3+ resonance
  - Direct capture
- 3+ resonance found to lie above the Gamow window in novae.

- Energy resolution and spin-parity assignments are crucial.
- 9 studies, e.g.  $^{20}\text{Ne}(\text{p},\text{t})^{18}\text{Ne}$  and  $^{16}\text{O}(3\text{He},\text{n})^{18}\text{Ne}$ , failed to locate the first 3+ resonance in  $^{18}\text{Ne}$ .

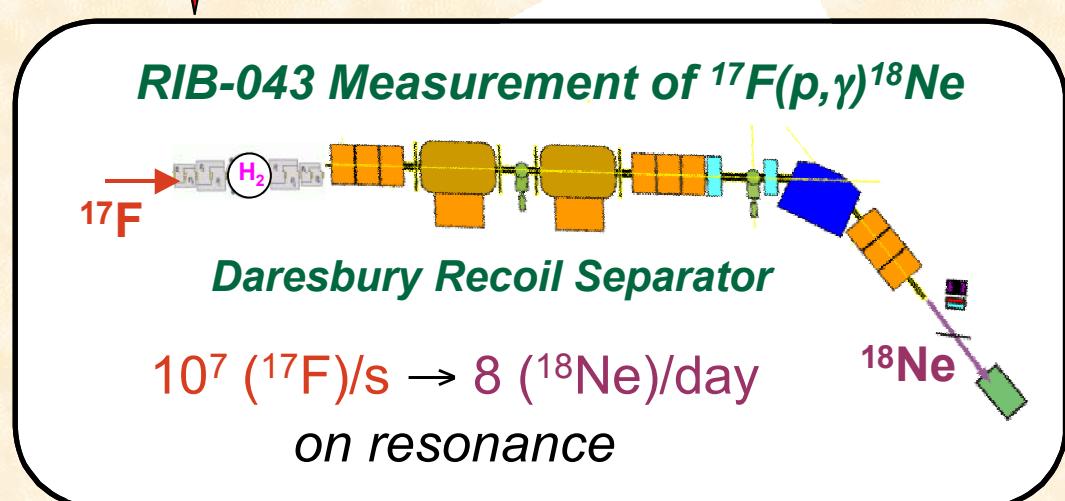


## resonant vs. direct



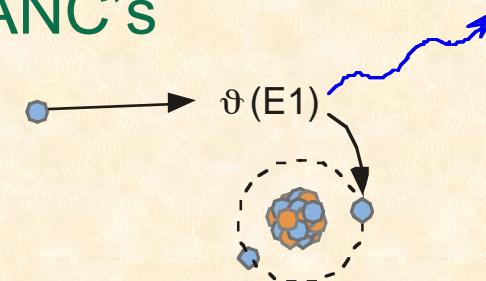
- Resonance strength of  $3^+$  is uncertain.
- Small contribution in novae, but important at X-ray burst temperatures.
- Approved experiment to directly measure the resonant cross section.

- Direct capture cross section is based entirely on structure of mirror nucleus  $^{18}\text{O}$ .
- Measurement of  $^{17}\text{F}(\text{p},\gamma)^{18}\text{Ne}$  at nova temperatures requires  $\sim 10^{10} ({}^{17}\text{F})/\text{s}$ .
- Indirect techniques required.



## Direct capture from ANC's

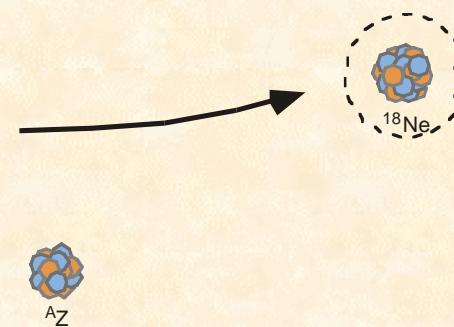
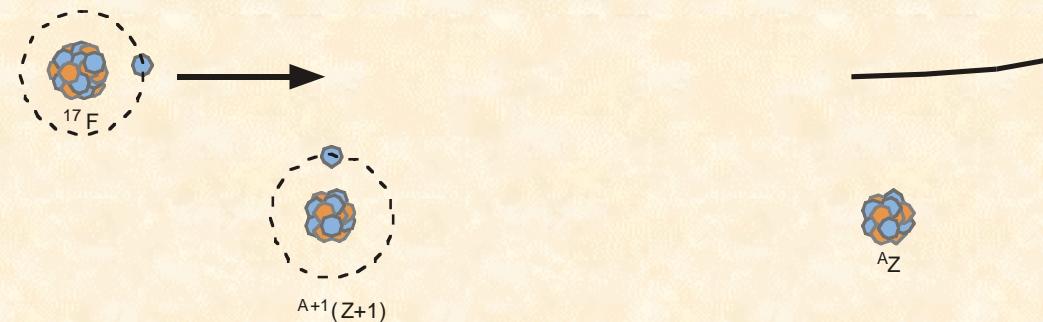
- Direct capture occurs via an electromagnetic transition at large radii.
- The cross section can be accurately calculated from the Asymptotic Normalization Coefficients (ANC's) with little model dependence.
- The ANC's can be determined by measuring the cross section for peripheral proton transfer reactions.
  - Mukhamedzhanov et al., PRC56 (1997) 1302.
  - Gagliardi et al., PRC59 (1999) 1149.
  - Gagliardi et al., Eur. Phys. J. A13 (2002) 227.



$$\sigma_{DWBA} \sim |\langle \chi_\beta \Psi_\beta | \Theta | \chi_\alpha \Psi_\alpha \rangle|^2$$

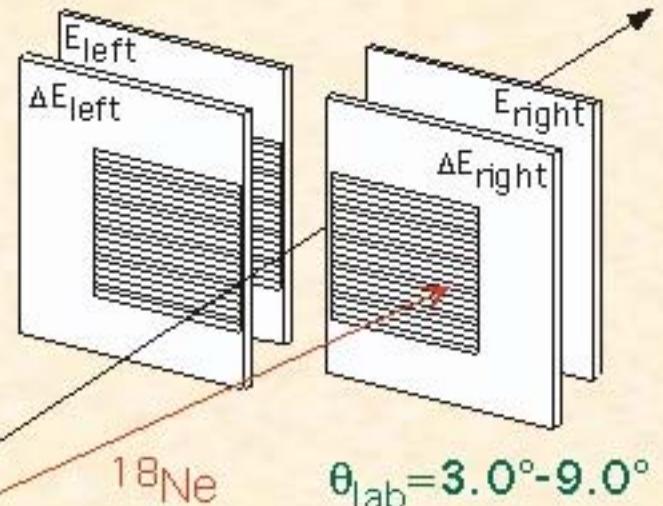
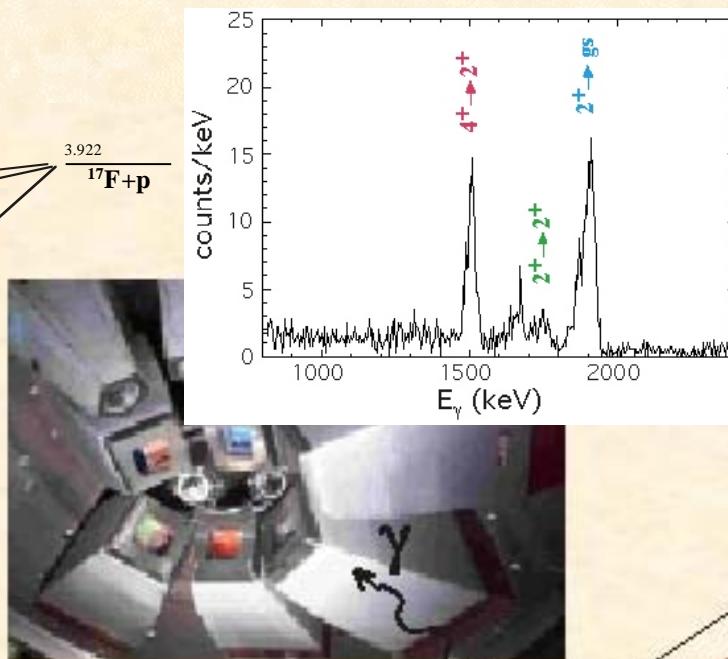
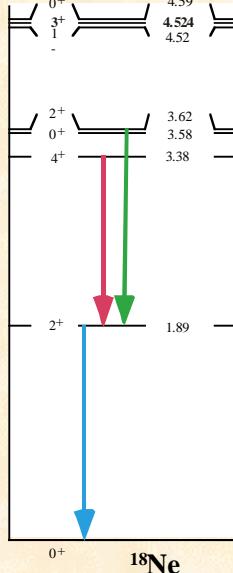
$$\Psi \sim \left(\frac{C}{b}\right) \varphi \quad \text{and} \quad \varphi \xrightarrow[r \gg R_a]{} b \frac{W}{r}$$

$$\frac{d\sigma}{d\Omega} = \frac{C_{Z+p}}{b_{Z+p}} \frac{C_{I^{17}F+p}}{b_{I^{17}F+p}} \sigma_{DWBA}$$



# $^{14}\text{N}(^{17}\text{F}, ^{18}\text{Ne}^*)^{13}\text{C}$ to determine $^{17}\text{F}+\text{p}$ ANC's

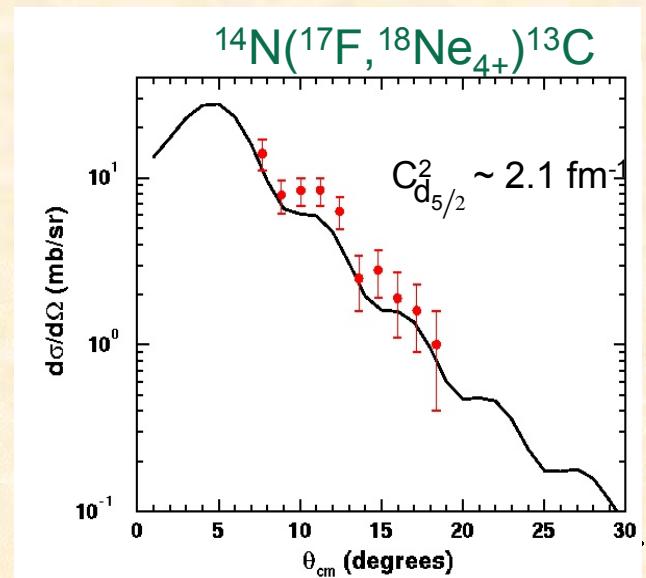
J.C. Blackmon *et al.*



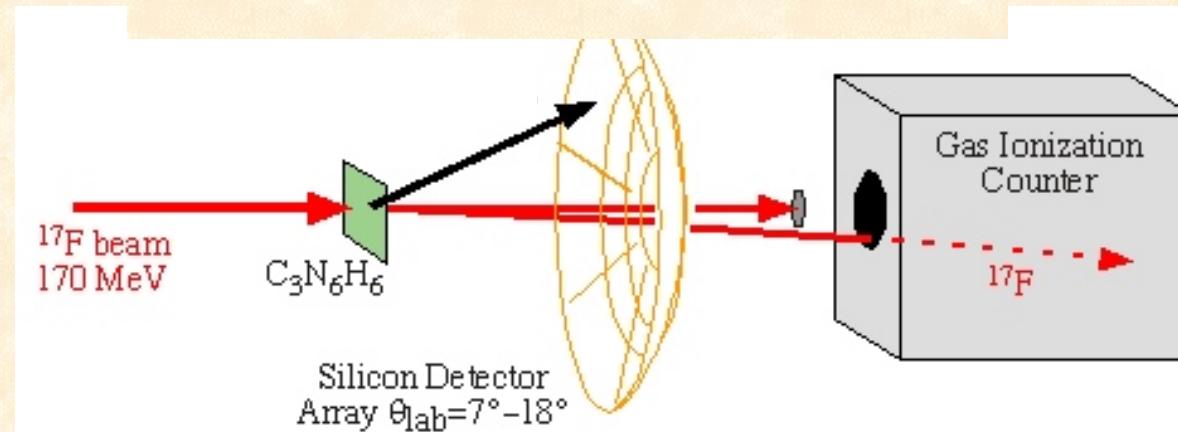
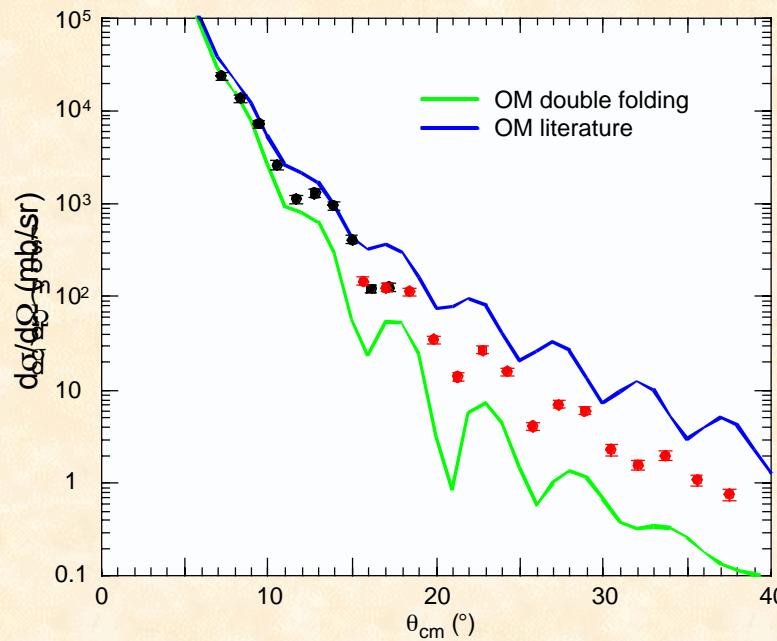
$^{18}\text{Ne}$        $\theta_{\text{lab}} = 3.0^\circ - 9.0^\circ$

$\text{C}_3\text{N}_6\text{H}_6$  target  
 $^{17}\text{F}$  Beam  
 (10 MeV/u)

- Gamma-rag tag used to resolve transitions of interest.



# Optical model parameters are important

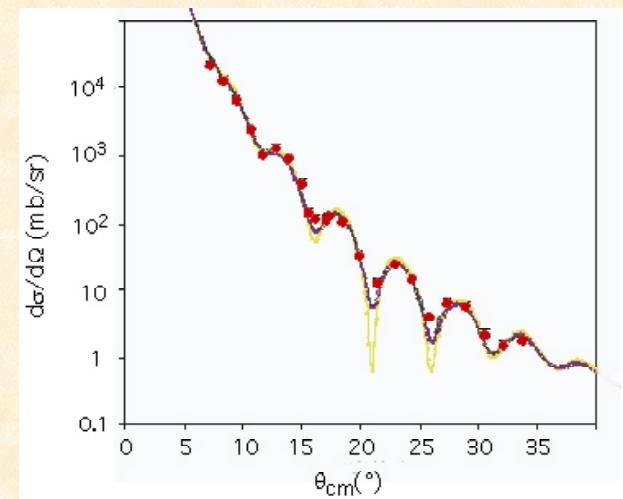
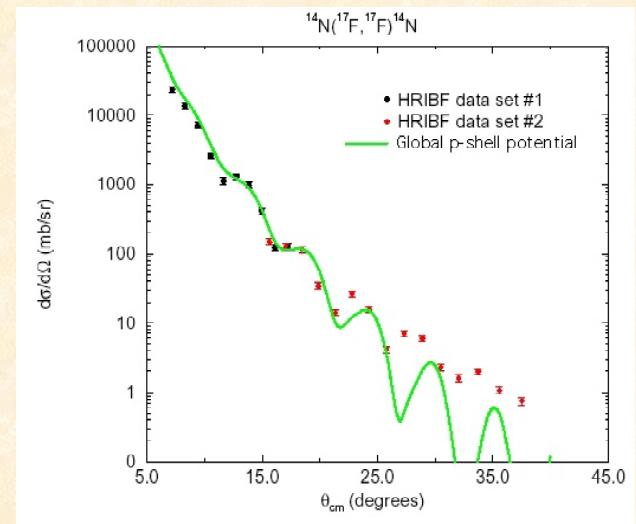


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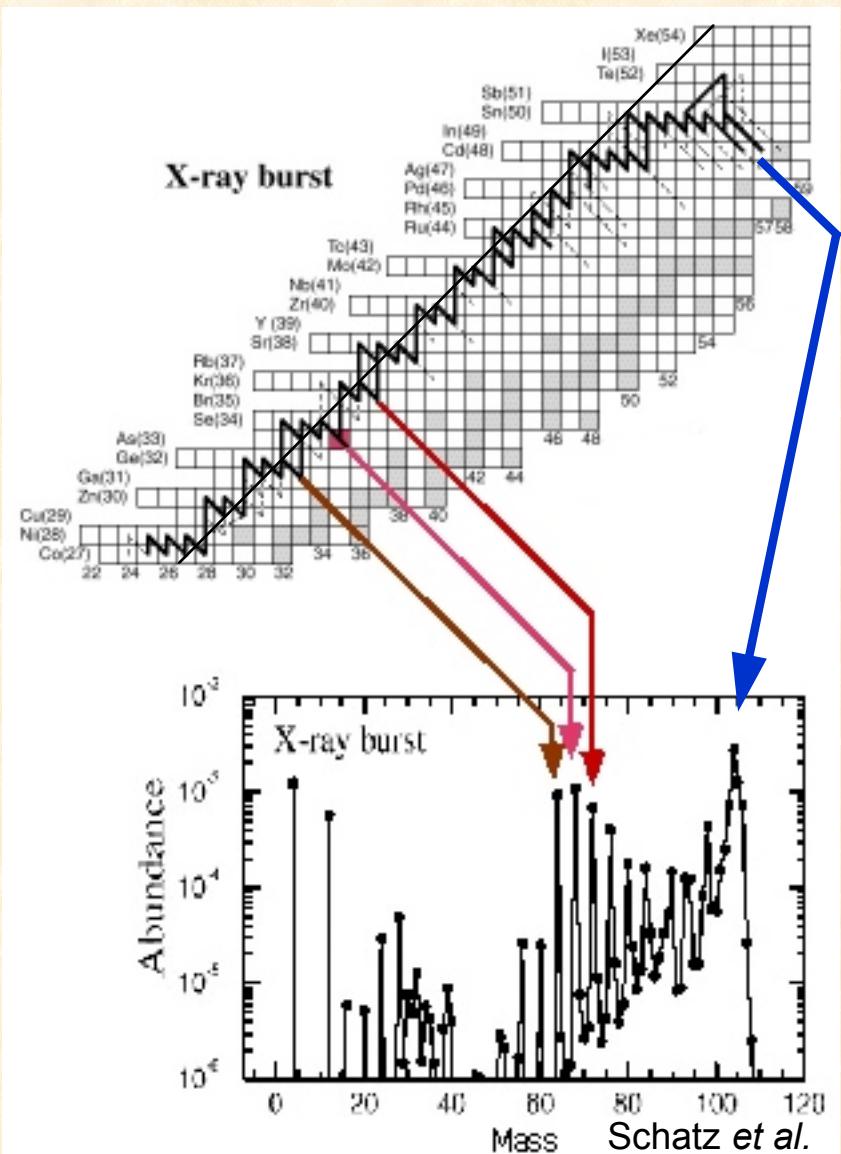
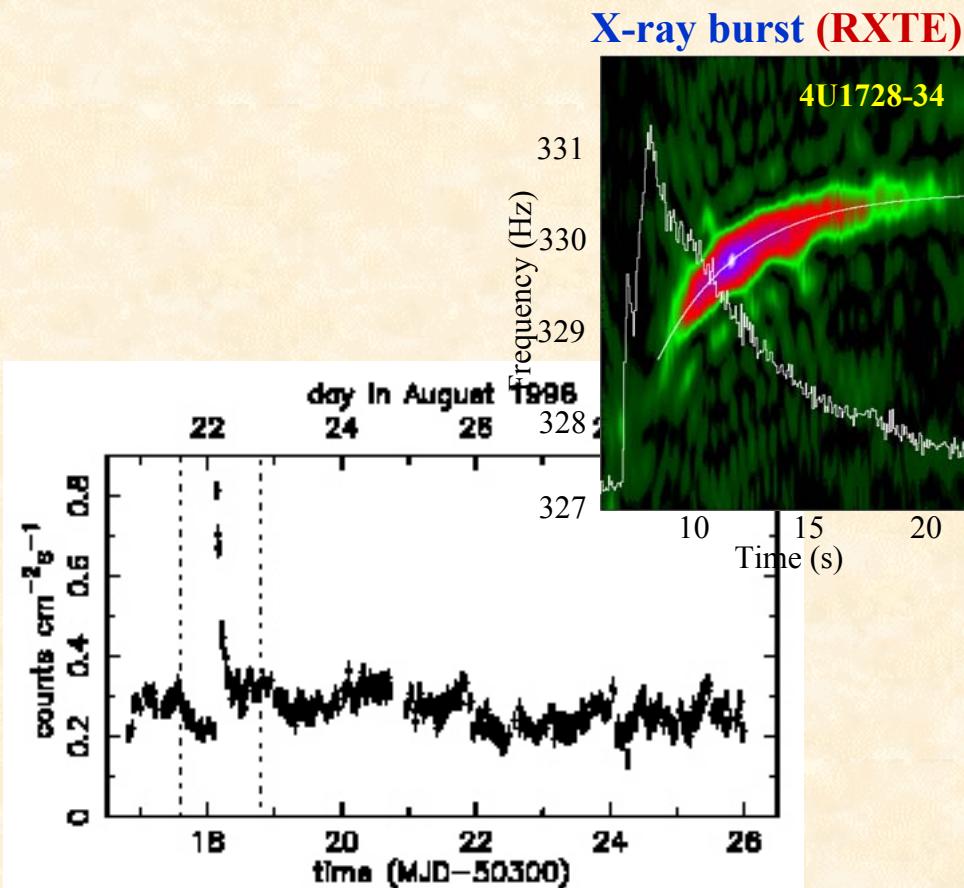
# Elastic scattering analysis

- Extensive study of p-shell nuclei at 10 MeV/u.
  - Trache *et al.*, Phys. Rev. C61 (2000) 024612.
    - $^{14}\text{N} + ^{13}\text{C}$
    - $^{10}\text{B} + ^{9}\text{Be}$
    - $^{13}\text{C} + ^{9}\text{Be}$
    - $^7\text{Li} + ^{13}\text{C}$
    - $^7\text{Li} + ^{9}\text{Be}$
  - Particle densities calculated from spherical HF.
  - Parameters of surface terms adjusted for correct binding.
  - G-matrix NN interaction
    - JLM *Phys. Rev. C16* (1977) 80.
  - Renormalization of folding form factor due to strong couple to breakup and transfer channels.
    - Real  $\sim 0.366 \pm 0.014$ ; Imaginary  $\sim 1.000 \pm 0.087$
- “Global” p-shell optical potential
  - Perform semi-microscopic analysis as above
    - $^{17}\text{F} + ^{14}\text{N}$  (Real  $\sim 0.606$ , Imaginary  $\sim 0.912$ )
    - $^{17}\text{F} + ^{12}\text{C}$  (Real  $\sim 0.530$ , Imaginary  $\sim 1.028$ )

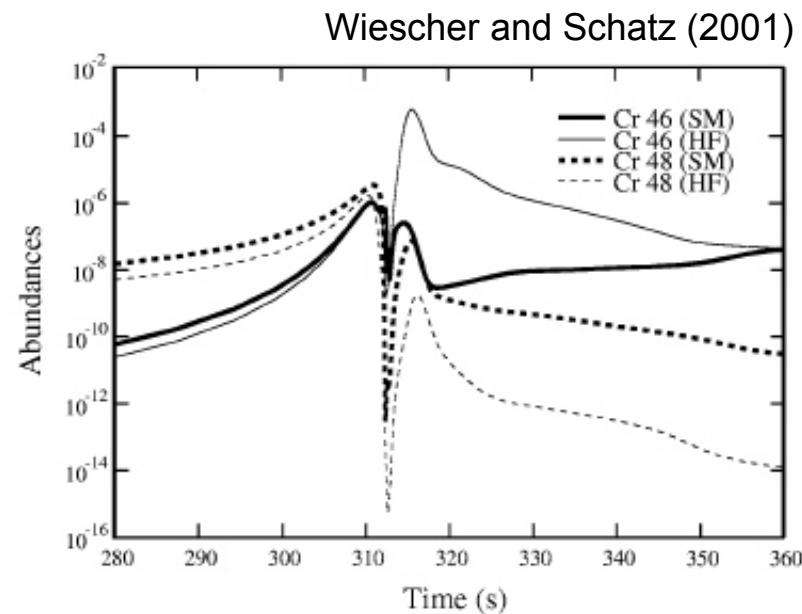


# X-ray bursts

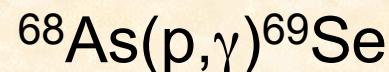
- Explosion on surface of a neutron star
- Significant variations in light curves
  - Superbursts
- Effects on neutron star composition
- Much more uncertain nuclear physics



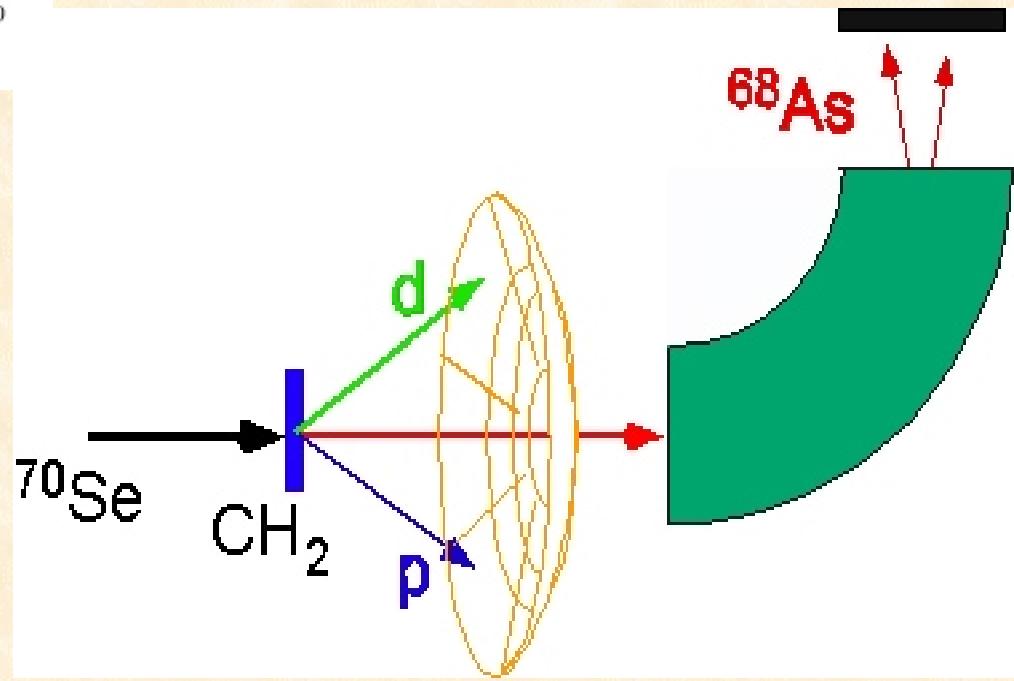
# Yields are sensitive to nuclear input



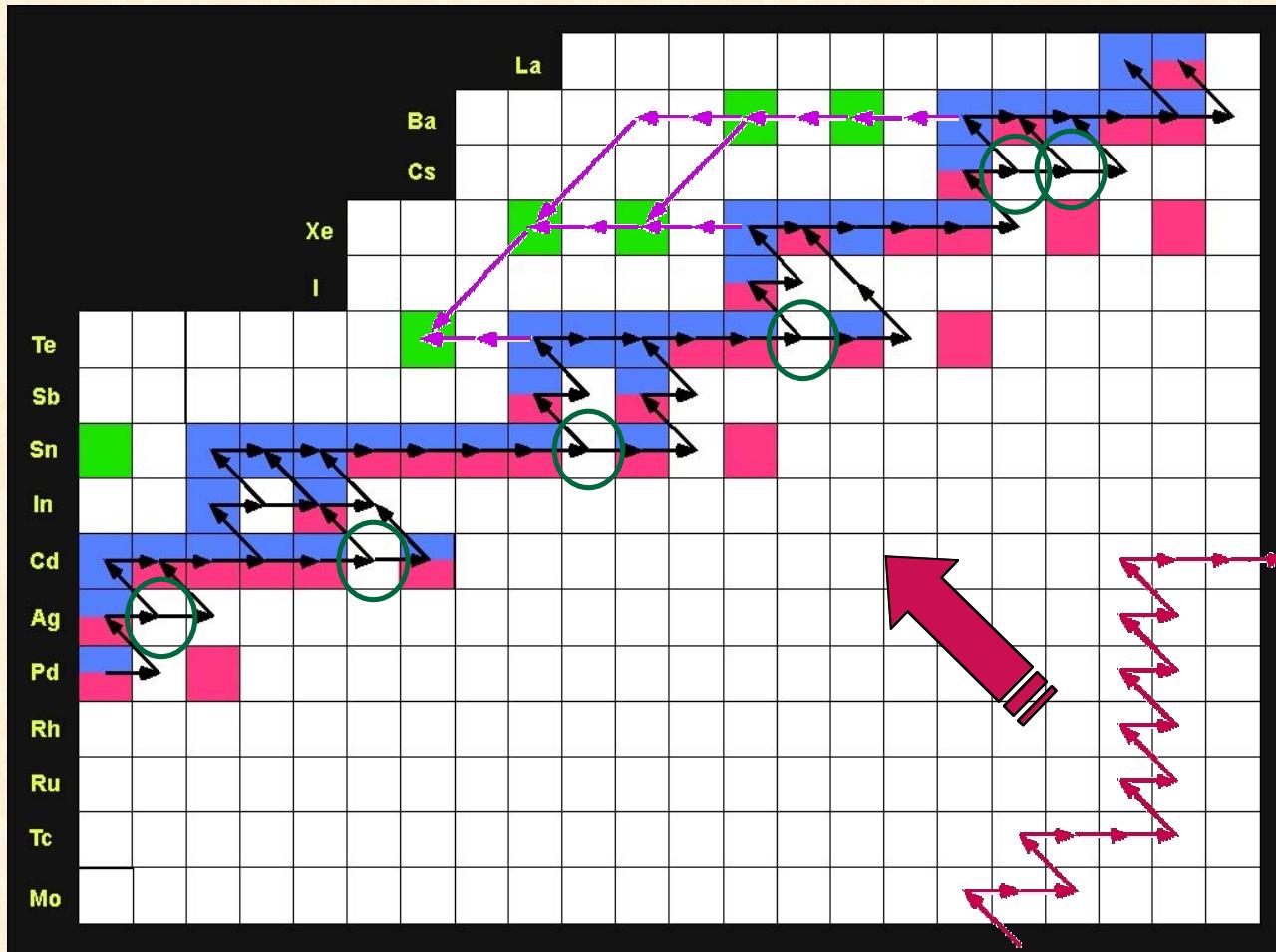
- Nuclei of interest are further from stability
- Small proton separation energies
- Low level densities
- Statistical model not reliable



- Proposed for MSU
- Use  $^{70}\text{Se}(\text{p},\text{d})^{69}\text{Se}^*$  to populate levels of interest
- Detect  $^{68}\text{As}+\text{p}$  in coincidence



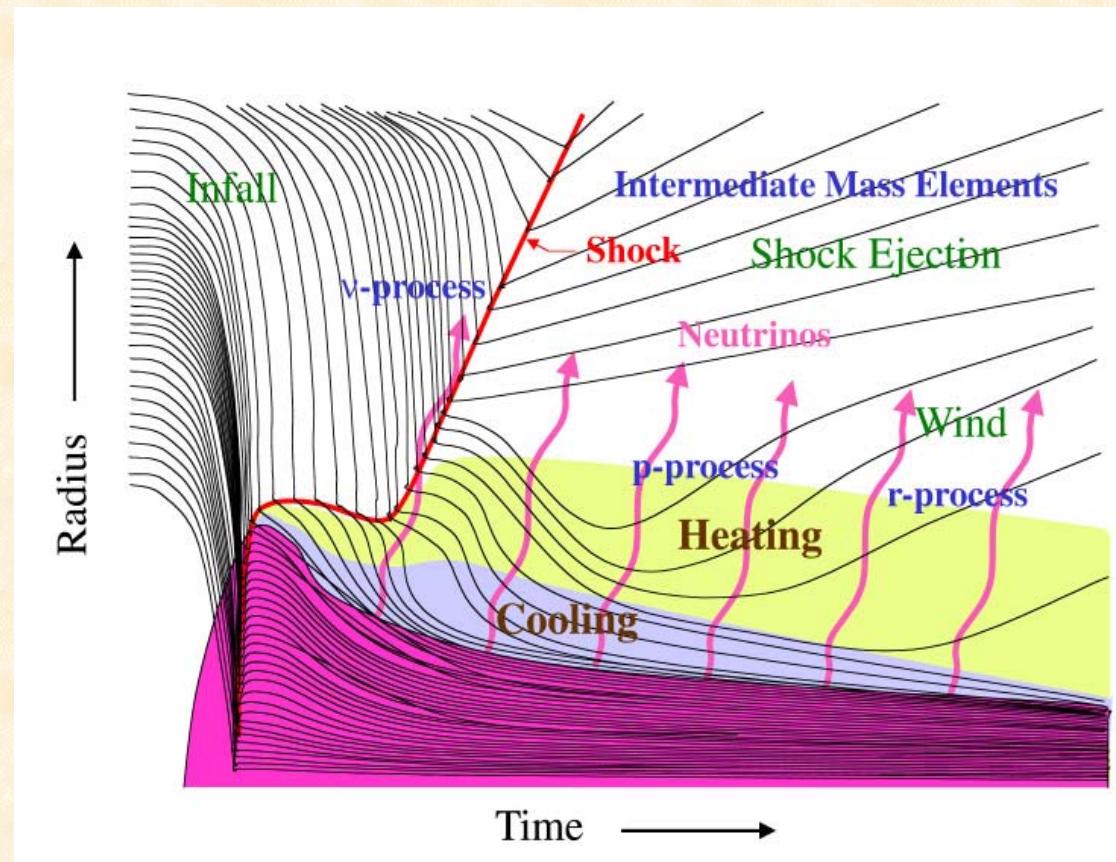
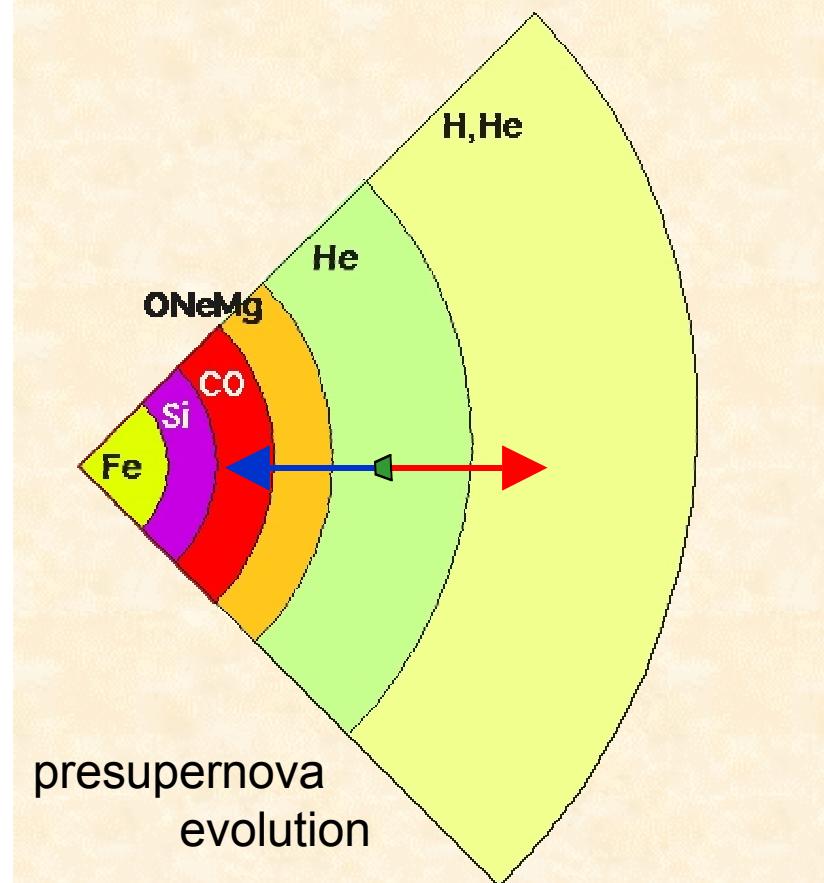
# *Synthesis of heavy elements*



- **s process**
  - ~ 80% of isotopes
  - ( $n,\gamma$ ) MACs needed
  - Branch points crucial
- **r process**
  - ~ 70% of isotopes
  - Far from stability
  - Need s abundances
- **p process**
  - ~ 10% of isotopes
  - Secondary process
  - ( $\gamma,\alpha$ ) cross sections
  - Need  $\alpha N$  parameters

# Supernovae

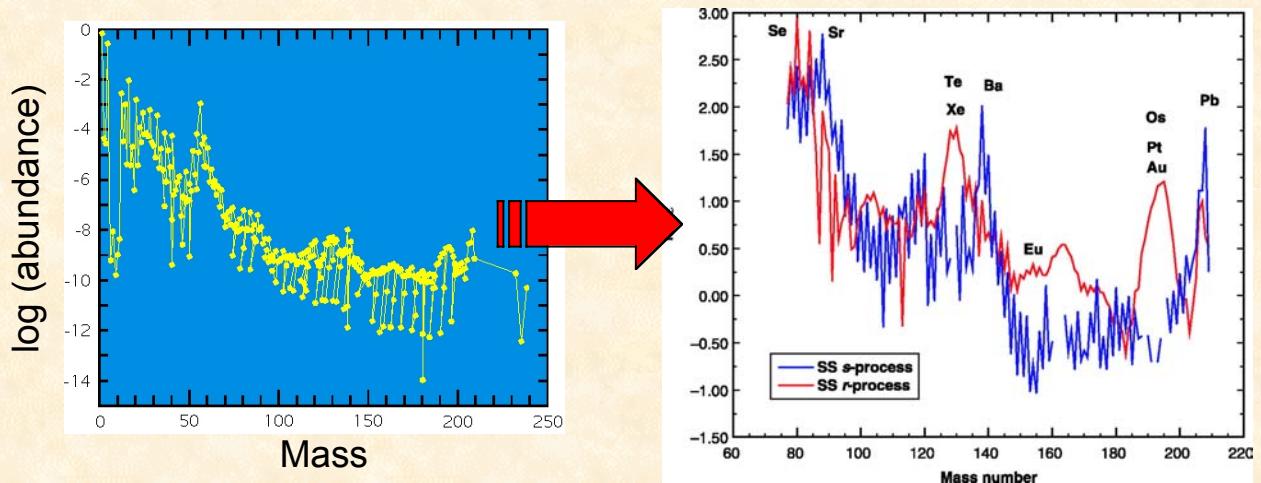
- » Core collapse of a  $10\text{-}25 M_{\odot}$  star
- » Outer layers ejected
- » Explosion mechanism not understood
- » Nucleosynthesis
  - Between shock and protoneutron star
  - High temperature, neutron-rich region



# What do we know about the r process?

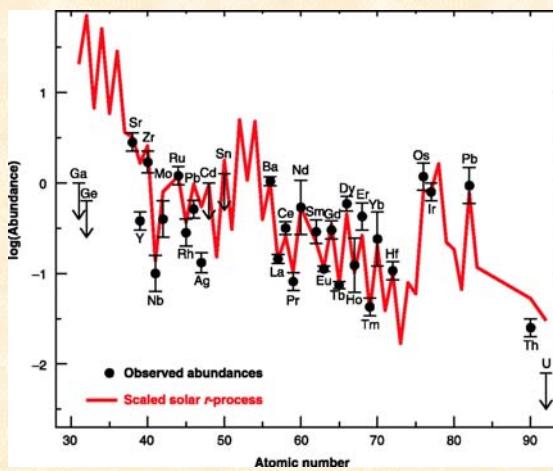
- “Solar” isotopic abundances

Anders & Grevesse (1989)



- UMP Halo stars

Sneden *et al.* (2000)  
Also Cowan, Beers, ...



Good agreement for  $Z=56-76$

Large variations for  $Z<56$

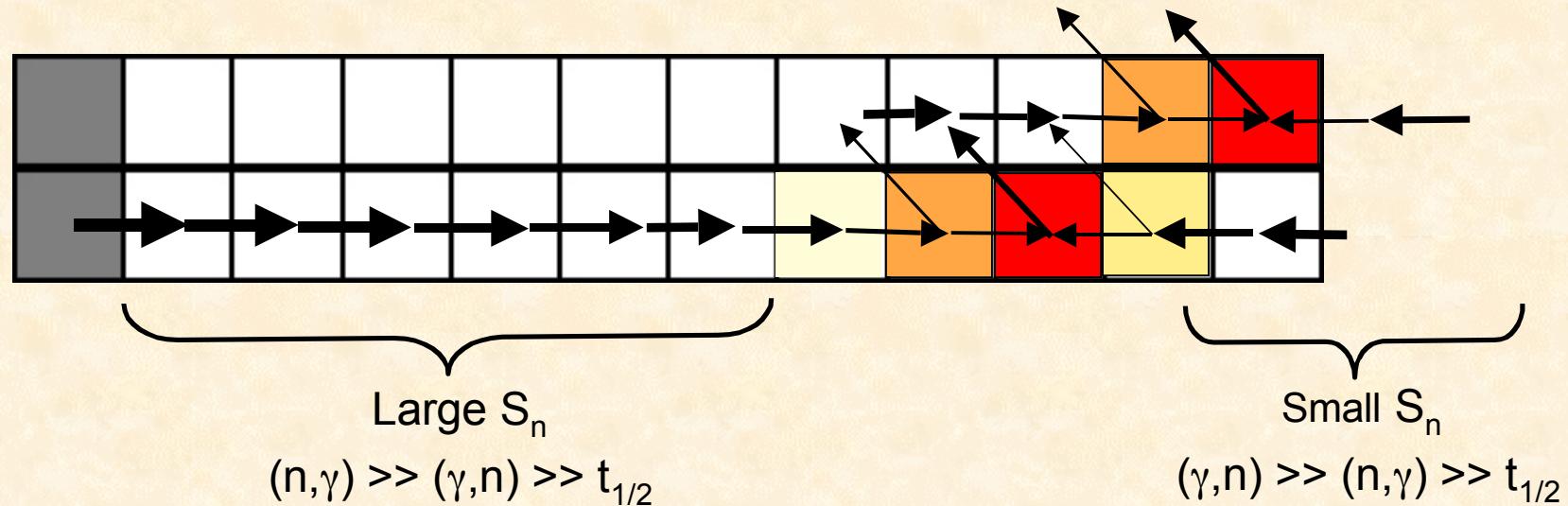
→ More than one r process

- Meteoritic measurements

No r process stardust (presolar grains)  
Some information from inclusions  
→  $^{182}\text{Hf}$  and  $^{129}\text{I}$  not likely to be coproduced

# Waiting-point approximation

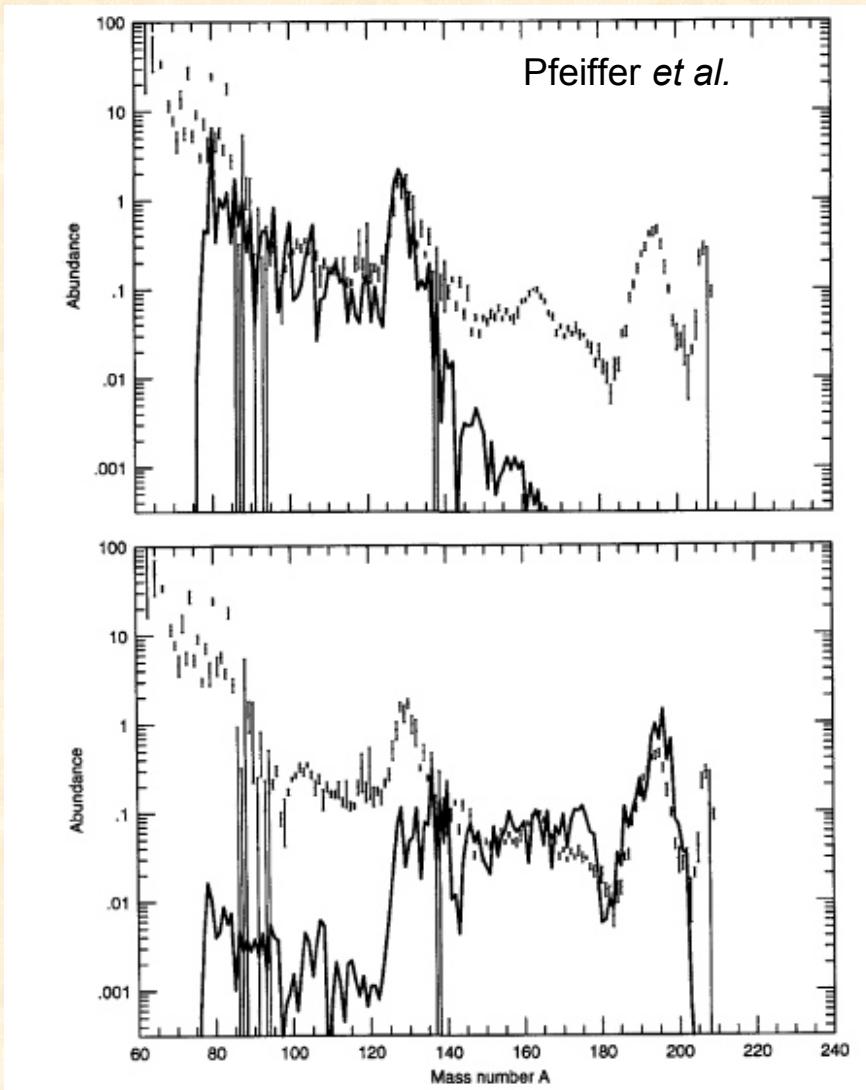
$$\frac{Y(A+1)}{Y(A)} \approx \frac{1}{2} \left( \frac{2\pi h^2}{m_u kT} \right) n_n e^{S_n/(kT)}$$



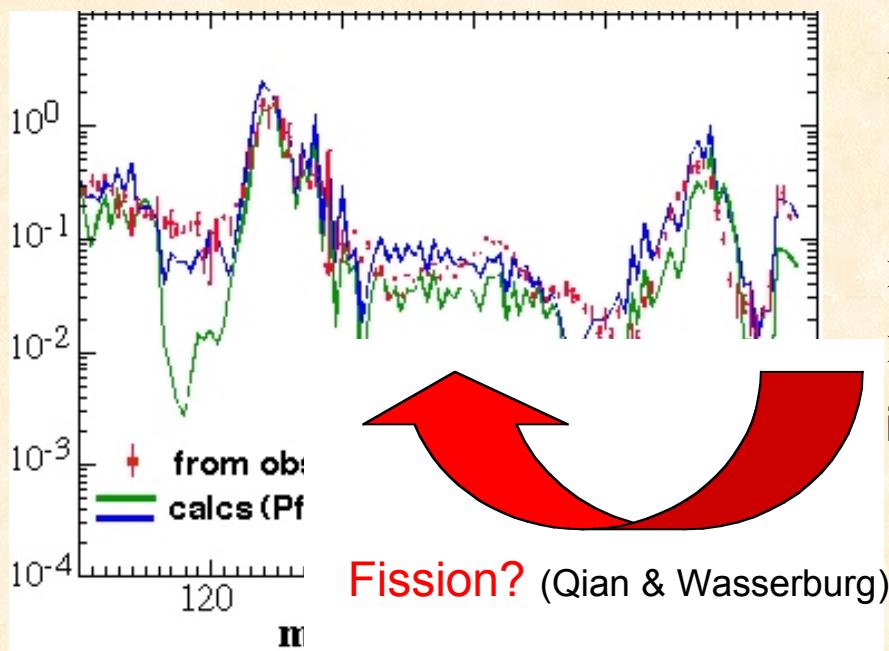
- Free parameters  $n_n, kT, t$
- Instantaneous freezeout & decay to stability

➡ Only masses,  $t_{1/2}$ , and  $P_n$  needed

# **$\geq 3$ components needed**



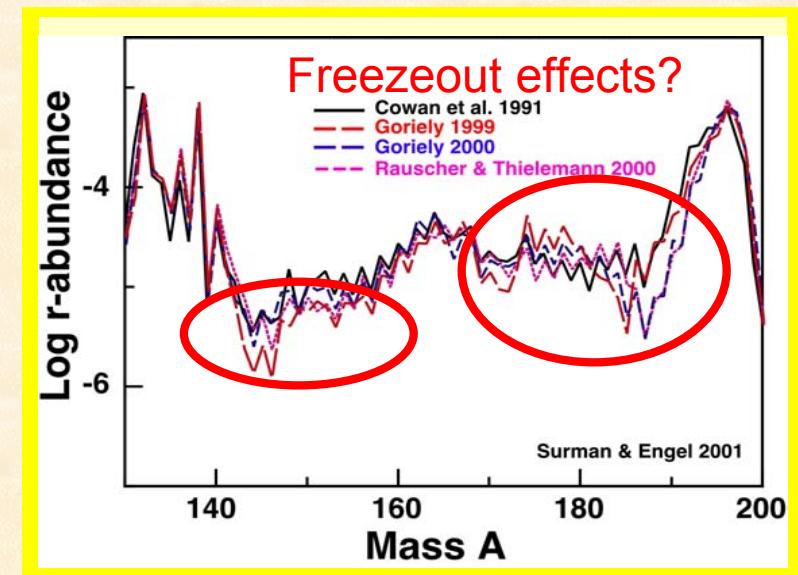
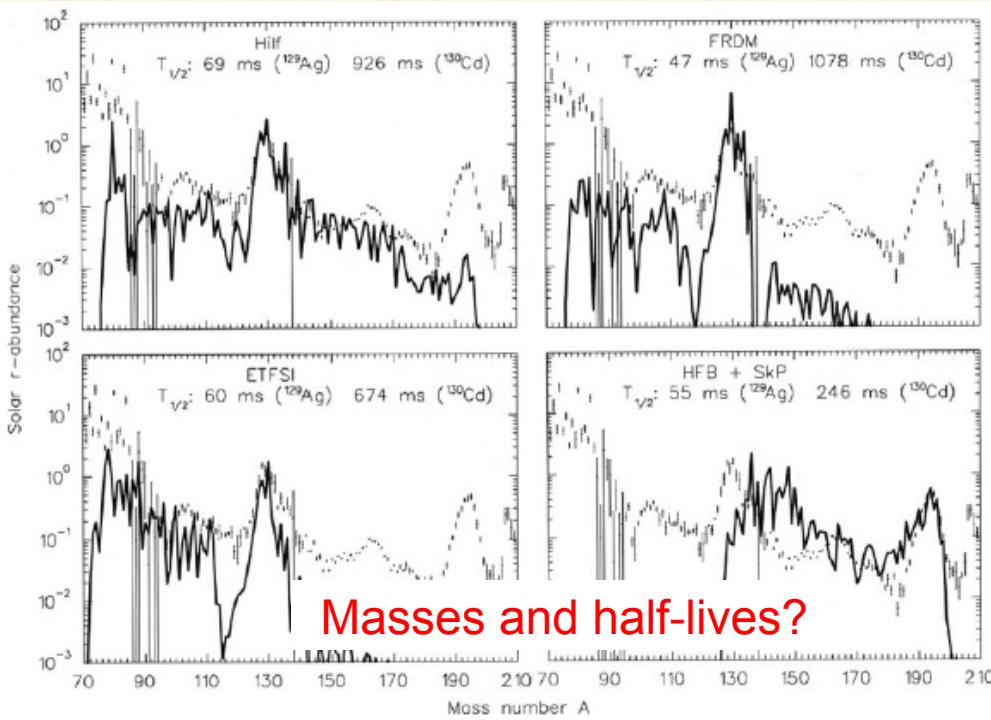
- $S_n = 2.7 \text{ MeV} (7\%)$   
 $\sim 10^{24} \text{ cm}^{-3} \times 2.2 \text{s}$
- $S_n = 3.3 \text{ MeV} (23\%)$   
 $\sim 10^{22} \text{ cm}^{-3} \times 1.6 \text{s}$
- $S_n = 3.8 \text{ MeV} (70\%)$   
 $\sim 10^{20} \text{ cm}^{-3} \times 1.2 \text{s}$



- More realistic models:  
Superposition of many components  
Adiabatic expansion of hot gas
- Reasonable fits to  $A=130,190$  peaks
- Not so nice reproduction of intermediate nuclei

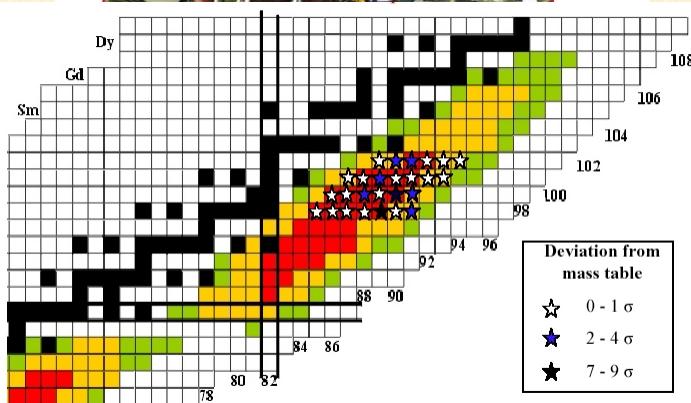
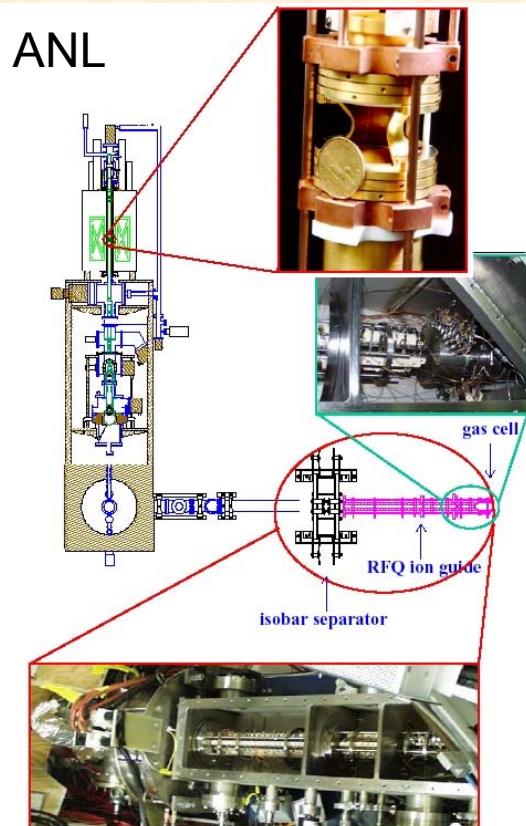
➡ Evidence for quenching of the shell gaps? (Kratz et al.)

Astrophysical environment?



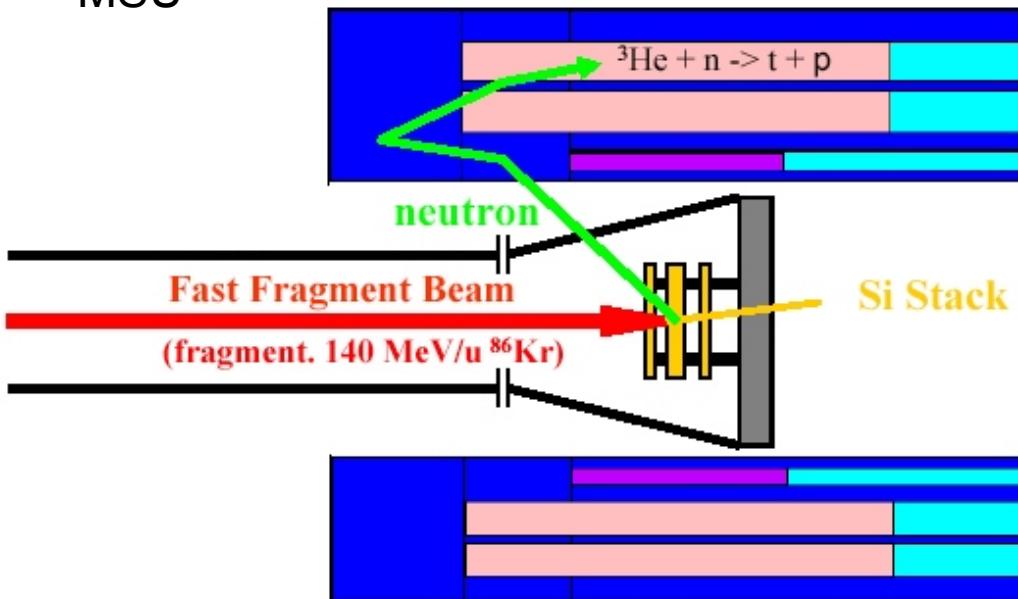
# Mass & decay measurements

CPT mass measurements



MSU

Neutron detector NERO



➤ In total ~ 30 r process nuclei have been studied in the laboratory

➤ Only ~ 10<sup>3</sup> to go

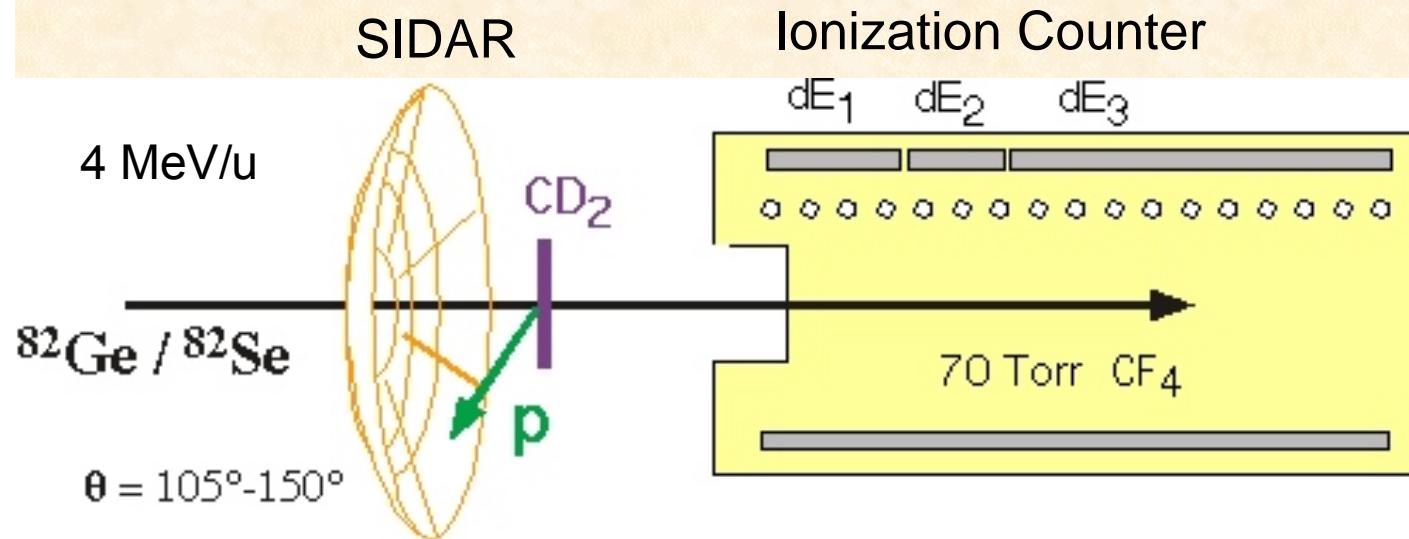
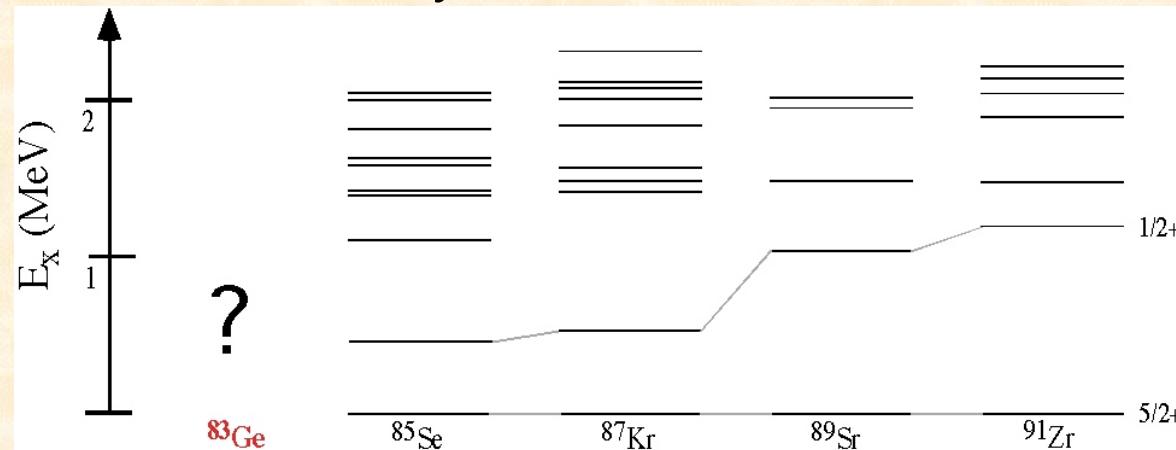
➤ Nuclear structure input important for improving predictive power of models

➤ B(E2), E(2<sup>+</sup>), S<sub>n</sub>

# Single-particle levels in N=51 Nuclei

J.S. Thomas, Rutgers Univ., Ph.D. Dissertation

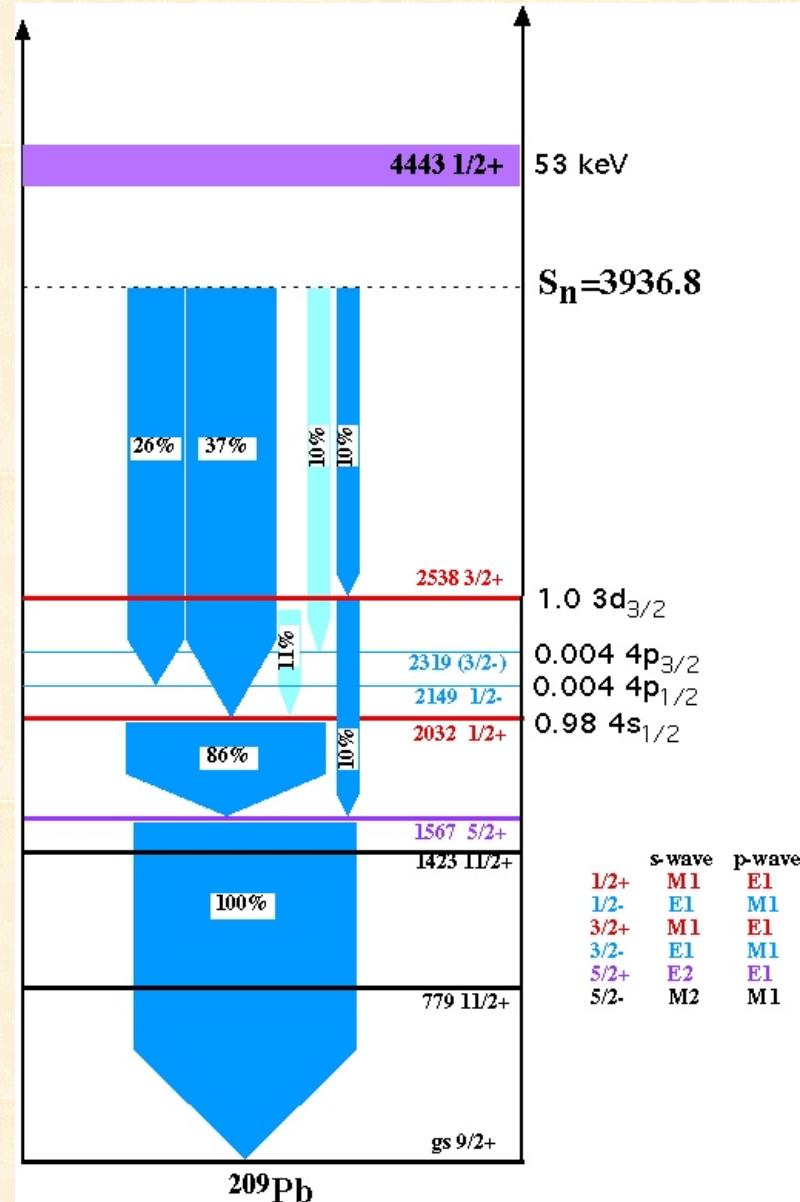
Half-life was only known information on  $^{83}\text{Ge}$ .



See talks by:  
Cizewski, Jones  
tomorrow

# $^{208}\text{Pb}(n,\gamma)$ thermal $\sigma$ from (d,p)

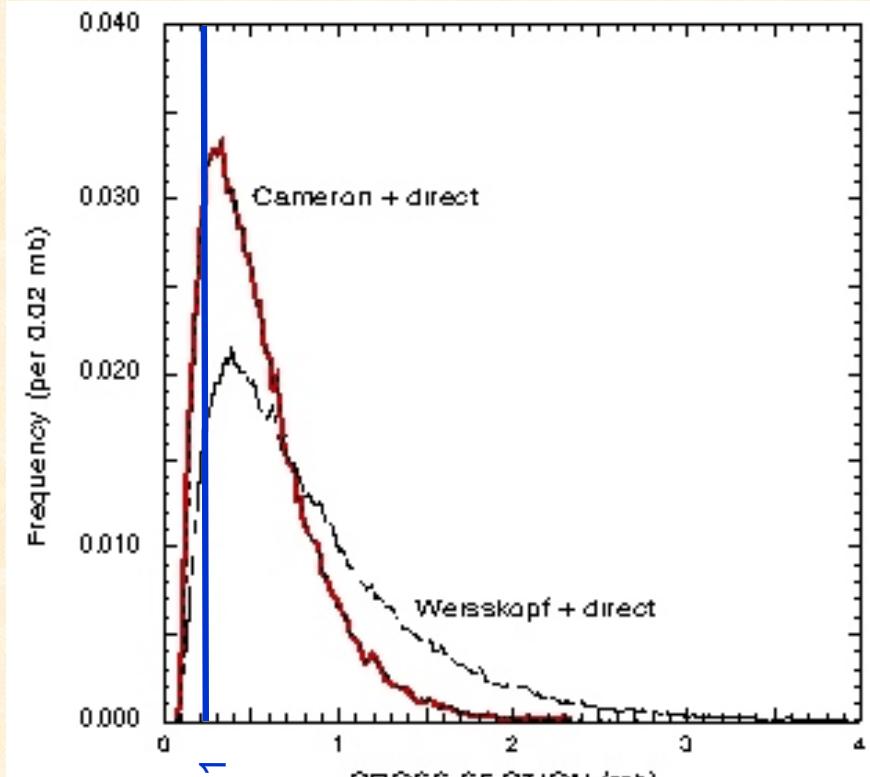
Blackmon *et al.* (2002)



➤ Low separation energy

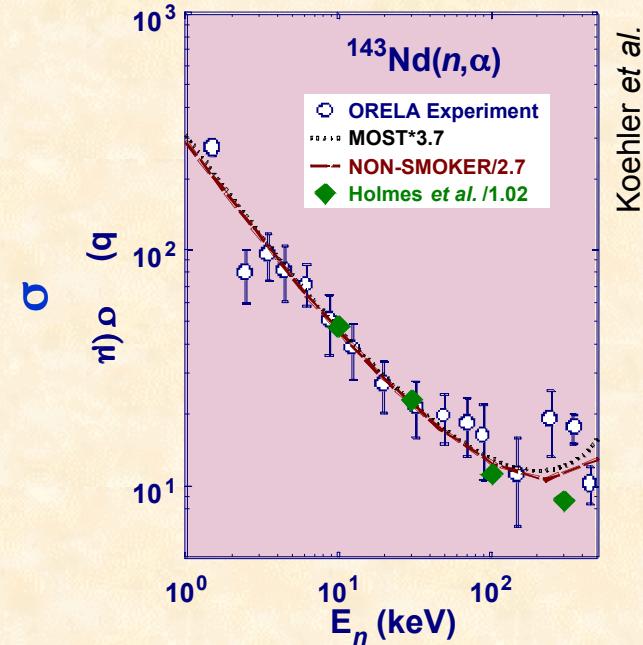
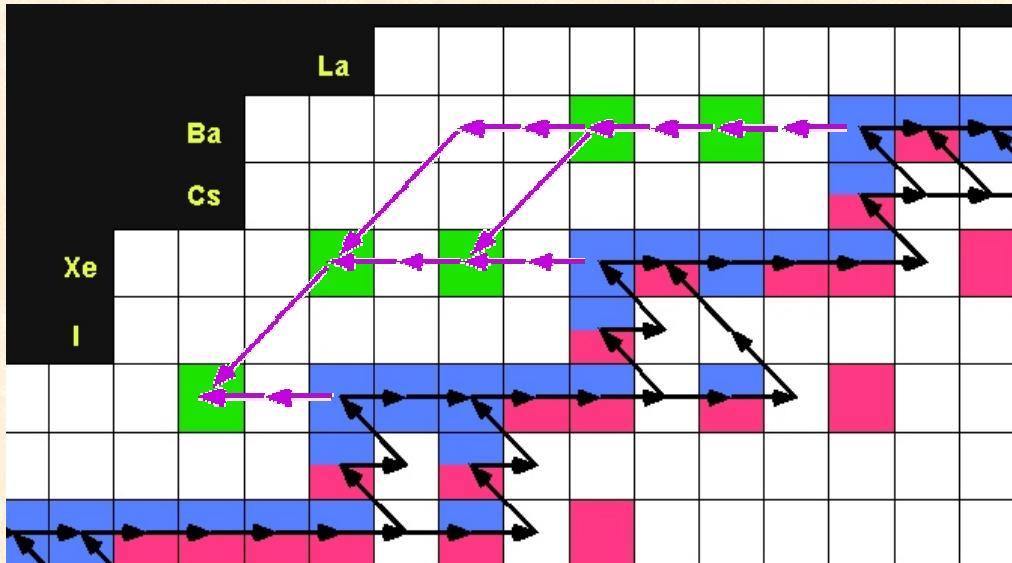
➤ Low level density

➤ Direct capture important



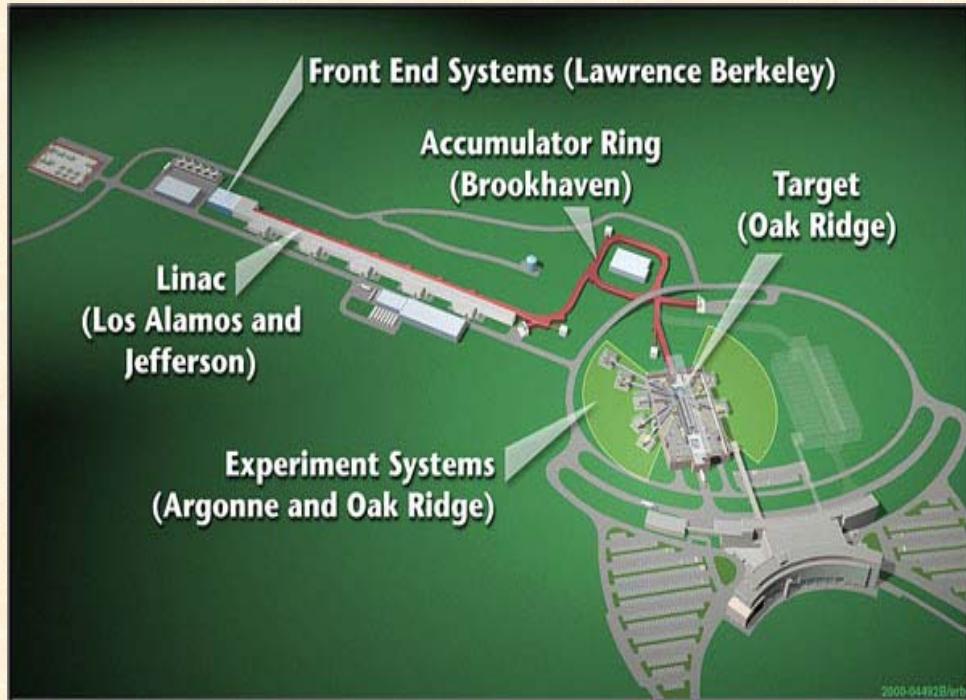
$0.23 \pm 0.01$

# The *p* process



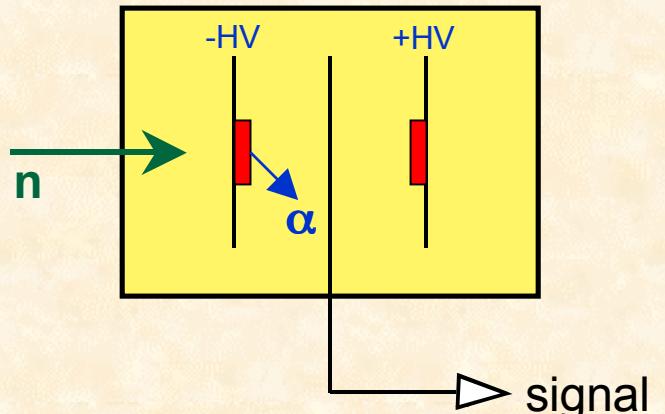
- Photodissociation of nuclei at high temperatures
- ( $\gamma, n$ ) and ( $\gamma, \alpha$ ) reactions most important
- Excited states are important
- Limited experimental guidance
- Largest model uncertainties - low energy  $\alpha N$  potentials
- ( $\alpha, \gamma$ ) measurements at low energies are very difficult

# **Measure $(n, \alpha)$ to better determine $(\alpha, \gamma)$**



<b>Source</b>	<b>ORELA</b>	<b>Lujan</b>	<b><math>n</math> TOF</b>	<b>SNS</b>
<b>flight path (m)</b>	40	20	180	20
<b>resolution (ns/m)</b>	0.2	6.2	0.05	18
<b>power (kW)</b>	8	64	45	2000
<b>flux (<math>n/s/cm^2</math>)</b>	$2 \times 10^4$	$5 \times 10^6$	$3 \times 10^5$	$2 \times 10^8$
<b>FOM (<math>n/s/cm^2</math>)</b>	$5 \times 10^5$	$6 \times 10^9$	$5 \times 10^8$	$9 \times 10^{10}$

gas ionization chamber



The SNS intensity will allow experiments with samples of only  $\sim 10^{16}$  atoms/cm<sup>2</sup>.

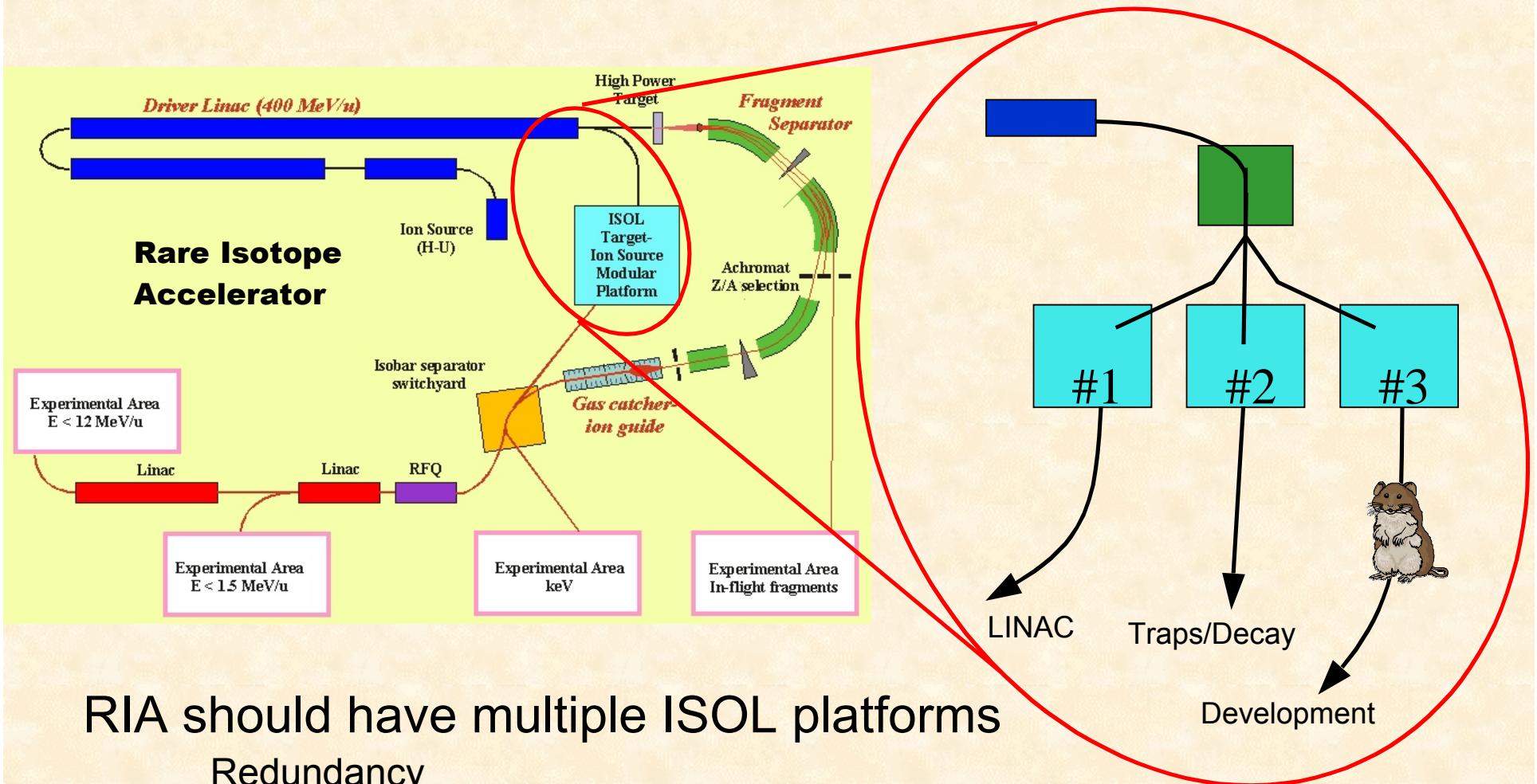
# *Isotopes for the p process*

Isotope	Half-life	Atoms required ( $10^{15}$ )	RIA intensity ( $10^9$ pps)	Other isotopes	Time Required (days)
<sup>53</sup> Mn	$3.7 \times 10^6$ y	200	2	Fe	1000
<sup>55</sup> Fe	2.73 y	200	2	Co	1000
<sup>57</sup> Co	272 d	200	2	Ni	1000
<sup>59</sup> Ni	$7.6 \times 10^4$ y	100	2	Cu	500
<sup>91</sup> Nb	680 y	40	2	Mo	220
<sup>92</sup> Nb	$3.5 \times 10^7$ y	20	2	Mo	110
<sup>93</sup> Mo	4000 y	40	3	Tc, Ru	150
<sup>97</sup> Tc	$4 \times 10^6$ y	20	3	Ru, Rh	75
<sup>109</sup> Cd	<b>461 d</b>	<b>8</b>	<b>500</b>		<b>0.2</b>
<sup>137</sup> La	$6 \times 10^4$ y	14	10	Ce-Pm	16
<sup>133</sup> Ba	<b>10.5 y</b>	<b>20</b>	<b>80</b>	--	<b>3</b>
<sup>139</sup> Ce	138 d	20	20	Pm, Sm	12
<sup>143</sup> Pm	<b>18 y</b>	<b>9</b>	<b>200</b>	<b>Sm, Eu</b>	<b>0.5</b>
<sup>145</sup> Pm	<b>1.7 y</b>	<b>6</b>	<b>100</b>	<b>Sm</b>	<b>0.7</b>
<sup>145</sup> Sm	<b>340 d</b>	<b>6</b>	<b>100</b>	<b>Eu</b>	<b>0.7</b>
<sup>146</sup> Sm	<b><math>1 \times 10^8</math> y</b>	<b>25</b>	<b>200</b>	<b>Eu</b>	<b>1.4</b>
<sup>148</sup> Gd	<b>75 y</b>	<b>10</b>	<b>150</b>	<b>Tb, Dy</b>	<b>0.7</b>
<sup>150</sup> Gd	<b><math>1.8 \times 10^6</math> y</b>	<b>10</b>	<b>300</b>	<b>Tb, Dy</b>	<b>0.3</b>
<sup>154</sup> Dy	<b><math>3 \times 10^6</math> y</b>	<b>10</b>	<b>1000</b>		<b>0.1</b>
<sup>159</sup> Dy	<b>144 d</b>	<b>3</b>	<b>2000</b>	<b>Ho</b>	<b>0.2</b>
<sup>157</sup> Tb	<b>71 y</b>	<b>4</b>	<b>1500</b>	<b>Dy, Ho</b>	<b>0.03</b>
<sup>172</sup> Hf	1.9 y	10	20		6
<sup>195</sup> Au	<b>186 d</b>	<b>5</b>	<b>1000</b>	<b>Hg, Tl</b>	<b>0.06</b>
<sup>194</sup> Hg	<b>444 y</b>	<b>10</b>	<b>800</b>		<b>1</b>
<sup>202</sup> Pb	52500 y	10	1		100

OAK RIDGE NATIONAL LABORATORY  
U. S. DEPARTMENT OF ENERGY



# RATs (RadioActive Targets) at RIA



RIA should have multiple ISOL platforms

Redundancy

Most ISOL targets require limited beam power

→ Several simultaneous uses in ISOL mode

# Conclusion

- The study of nuclear reactions with radioactive isotopes is crucial to improving our understanding of novae, X-ray bursts, and supernovae.
- Reaction rates of interest are often dominated by isolated resonances.
- Direct measurements at astrophysically relevant energies is difficult.
- Surrogate reactions provide a powerful tool for extracting astrophysically important quantities.
- Measurements are being performed now with stable and radioactive beams.
- The viability of indirect methods for nuclear astrophysics depends greatly on the structure of the nuclei involved - particularly the particle separation energy and level density.